2015

Early-Stage Transition to Predictive Maintenance : Using CMMS, IR Scans, and Vibration Analysis to Improve Uptime and Lower Maintenance Costs

Jason Hamilton
Portland State University

Early-Stage Transition to Predictive Maintenance: Using CMMS, IR scans, and vibration analysis to improve uptime and lower maintenance costs.

by

Jason Hamilton

An undergraduate honors thesis submitted in partial fulfillment of the
requirements for the degree of
Bachelor of Science
in
University Honors
and
Mechanical Engineering

Thesis Adviser
William Eisenhauer

Portland State University

2015

Contents

Table of Figures

Executive Summary

Implementing a predictive maintenance model does not have to be a five year, million dollar project. There are relatively simple steps a maintenance team can take to see results within the first year. Because overall cost of predictive maintenance is up to four time less expensive than preventative maintenance, as many assets as possible should be covered by predictive maintenance. Facilitating the transition to predictive maintenance is made easier with a Computerized Maintenance Management System. A good CMMS is user-friendly, automatically produces preventative maintenance work orders, and tracks all work done on each piece of machinery. IR scans and vibration analysis are two predictive maintenance techniques that can increase uptime. IR scans are an effective way to find loose or dirty electrical connections before they cause machine down time. Vibration analyses show bearing faults before the bearing locks up and destroys the journal.

Fitesa Washougal is a single machine non-wovens facility in Washougal, Wa. In July 2014 the maintenance team at this facility implemented a new predictive maintenance model. A new CMMS was purchased to better manage assets and preventative maintenance activities. Vibration analysis was contracted to an outside company, and is now done monthly. IR scans are done in-house, with each cabinet in the program scanned quarterly. These actions have resulted in a 3.5% increase in uptime. Maintenance spending increased by 31%, but unplanned maintenance downtime decreased by 34%. The net impact on the company is a savings of $267,000 for the first year of the program.

Introduction

When most people think of a manufacturing environment they picture the best case scenario. The machine is spinning, the operators are calmly running the equipment, and good product is being made. The reality of most manufacturing environments is far from this picture. All too often the machine is down, technicians and engineers are desparately troubleshooting the problem, and the plant manager is reminding them how much money the plant is losing per hour.

Until recently, maintenance departments have employed a strategy of only working on the machine when it is broken [12]. This is frequently called Run to Failure (RTF), or in the colloquial, “if it ain’t broke, don’t fix it”. This kind of “reactive” maintenance costs two to four times as much as “proactive” maintenance [16]. This led companies to shift from RTF to Preventative Maintenance (PM), where the machine is taken down on regular intervals for the mechanics to work on it. PM work can get a company to about 80% proactive (scheduled) maintenance [16].

To get to the goal of 90% proactive maintenance, it has become increasingly necessary for companies to use Predictive Maintenance (PdM) [12]. Unlike PM, where work on the machine is dictated by time, with PdM the condition of the machine dictates the work. The machine condition is tracked and plotted to find trends. When a certain trigger level is reached for the machine, the work can be scheduled on the next shutdown. Machine condition can be collected in numerous ways; however, the most common are: vibration analysis for rotating parts, IR scans for electrical equipment, and oil analysis for lubricated parts [11].

All maintenance managers have heard of predictive maintenance. Often, they hear it from their boss, who has some knowledge about the impact and then dictates a switch to a predictive maintenance model. In small to medium production facilities this directive often comes with no additional personnel and no additional funding. Results are also expected by the end of the month. These kinds of directives stem from a fundamental lack of understanding of just how enormous of a technical and cultural transition is needed to go to a PdM model. The change can take 3-5 years, and often results are not seen in the first year [11].

This task can seem overwhelming; especially to a maintenance team that experiences constant breakdowns (why else would the plant manager want to change the model?). This paper intends to remove some of the burden by describing some relatively simple maintenance activities to aid in the switch. These include using a CMMS, performing vibration scans, and performing IR scans. The aim of this paper is not to provide an exhaustive roadmap for implementing a “World-Class Maintenance” program, but to give some steps that can be taken immediately to improve uptime. For example, vibration scans are an extremely effective tool for finding bearing faults. Buying hundreds of permanently mounted accelerometers with a couple terminal stations can cost hundreds of thousands of dollars. At the other extreme, having a technician come in twice a year to scan only a couple of bearings will never allow a company to predict failure; only find it once it has occurred. But there are alternatives that that provide results with less cost.

In 2013 Fitesa Washougal, Inc. had a PM program, but none of the PMs were being tracked. There was a huge amount of "tribal knowledge" from the "old-timers" who knew when to lubricate what equipment based on experience. The Computerized Maintenance Management System (CMMS) was only used for storeroom inventory. There had been a small amount of PdM activity in the past (once a year someone would do an IR scan and a vibration analysis), but they were not being done regularly enough to see the benefits.

This paper will first analyze the financial impact on a business deciding to improve their current maintenance department by using PdM. Many companies currently have a set schedule for doing Preventative Maintenance, and this paper will explain why it is important to shift from time based repair to condition based repair. The next section of the paper will use literature readily available to any maintenance engineer to lay out a roadmap for facilitating that shift. This will include different approaches and justifications for upgrading the CMMS, performing IR scans, and performing vibration analysis. The next section will prove the hypothesis by doing a case study on a non-wovens plant owned by Fitesa, Inc. The case study will analyze the PdM activities undertaken by Fitesa's Washougal plant, and look at how the new model affected key performance metrics. Finally, the next steps to improve on the PdM program will be outlined.

Review of Literature

Most manufacturing plants have moved from a "Run to Failure" (RTF) maintenance strategy to a "Preventative Maintenance" (PM) strategy [11]. A well-developed PM program is a critical step to becoming a top performing maintenance department [16]. To set up a good PM program, it is necessary to review the manuals on the plant equipment. These manuals will give service life, lubrication intervals, and recommended lubricants, among other useful information. The maintenance technicians should be able to provide a detailed list of the types of work they regularly do on each asset. Both sets of information are used to generate a comprehensive list of time based maintenance activity. This list should be entered into the CMMS, which will automatically generate PM work orders at the intervals specified. The PMs must always be "quantifiable" [1]. For example, the maintenance technician might already check the belt tension by hand on a certain piece of machinery every week. This work must be changed to have the technician check the belt tension with a tension gauge and record it. The values can be tracked in a CMMS and used to schedule belt replacement on a machine shutdown.

Not every maintenance task; however, should be time based. Because PM programs are so effective at maintaining asset life, managers have been wrongly using them to determine when to change assets [14]. Changing assets on a routine schedule, before failure, is expensive and causes unnecessary downtime. Figure 1 shows traditional failure modes and the percent of equipment they are accurate for.

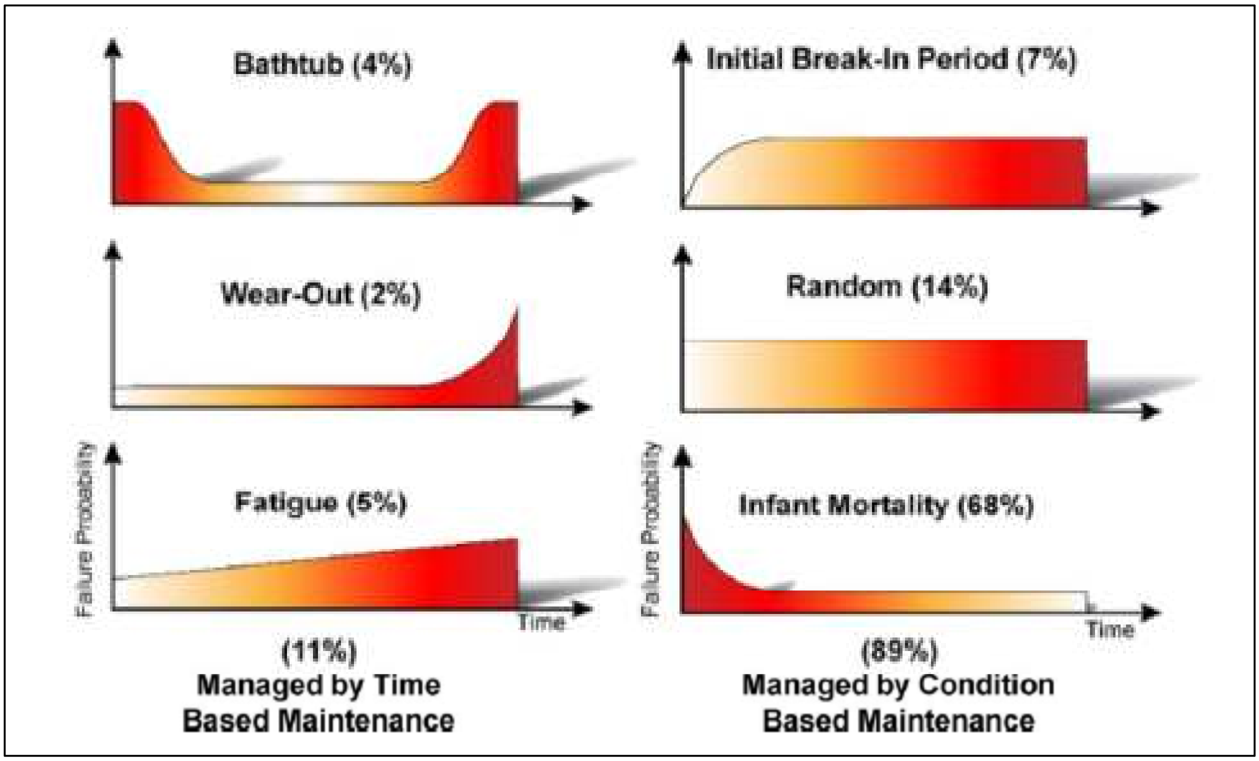


Figure 1.Traditional failure modes and their accuracy. The graphs on the left illustrate which failure modes are solved with a PM program. The graphs on the right, PdM program. Taken from Fig. 2 in "State-of-the-Art Predictive Maintenance Techniques" [4].

According to Fig. 1, only 11% of assets have life that is predicted by a PM program. Instead, companies need to determine when to change assets based on condition, not service time. Estimates on how much money this can save a company vary widely. Jerry Pinkard of Management Resources Group (MRG), a reliability services company owned by Emerson

Process Management, says condition based maintenance is 42% less expensive than time based maintenance [14]. Timothy White of the same company puts the number at 25% [15].

Once the case has been made to upper-level management for the need to implement a PdM program, a team should be created to spearhead the project. Determining who should be on this team is a crucial step in the process. It is important to select people from both management and staff, who are "analytical in nature..., detail oriented..., and computer savvy" [5]. There is an instinct to include many of the "old-timers" who have the most experience with the equipment; however, they are often "set in their ways" and may not offer as much value as the newer technicians.

Once the team has been selected, it is important to evaluate the current state of the site's Computerized Maintenance Management System (CMMS). Most companies already have a CMMS; however, over half of companies either do not like or have no opinion of their CMMS [7]. The financial case for implementing a new or better CMMS is overwhelming. Keith Mobley, who has written several books on PdM, claims there can be a 16%-50% reduction in maintenance costs with a good CMMS [11]. Mike Crain of MRG puts the number at 10-30% [2]. The most important attribute to any CMMS is user-friendliness. The ultimate goal is that everyone in the company (managers, operators, technicians, etc.) will enter and retrieve information from the CMMS. Most companies that buy a different CMMS are moving to a more user-friendly system [13]. After the proper CMMS has been selected and the team trained on its use, it is time to start populating the system.

Populating the CMMS is painstaking, repetitive, and arduous work. For these reasons, it is all too easy to skip over the important details. The first step is listing the company's assets in an asset tree. There will be a tendency here to list just the major assets, or the assets that fail the most often; however, every attempt should be made to include all of the assets in the plant. Rusten Smith of MRG stresses the importance of adding Bills of Material at this stage. Each Bill of Material (BOM) should be separated into parts that are kept in the storeroom and parts that are not. Some manufacturers give expected life for their parts, and this information can be used to determine what parts should be stocked. MRG has found that implementing a BOM best practice strategy can contribute to savings of 30% [15].

One of the most important roles of the CMMS is work order generation. Work orders can generally be divided into two categories: scheduled and unscheduled, although every attempt should be made to further subdivide those categories (safety, environmental, predictive, preventive, etc.). Most experts on the subject have come to a consensus on some basic rules for a work order system: do not work without a work order, tie each work order to an asset, list all parts needed for the work, estimate (and then confirm) the amount of time required for the job, and generate scheduled work orders automatically [17]. For PM tasks this is done with a time trigger, and for PdM tasks it is done by a condition, or metering, trigger (temperature, vibration data, and contaminant level).

With the foundation in place, it is finally time to collect the data used to predict failure. If a piece-wise implementation is desired, the most logical place to start is vibration testing on rotating machinery. The leader of the PdM program must decide whether vibration testing will be done internally or by an outside company, and whether data will be collected with a handheld device or permanently installed accelerometers. According to Keith Mobley, the average price for a permanently installed device is "$300 per measurement point" [11]. No matter how the data are collected, it must be stored in the CMMS system. Data collection should not follow a routine schedule, rather as the data show declining condition of the asset, data collection frequency should increase [5]. Mobley provides a general guideline for trigger levels in vibration analysis, shown in Fig. 2.

Table 7–2 Vibration-Severity Standards (Inches/Second-Peak)				
	Machine Classes			
Condition	**I**	**II**	**III**	**IV**
Good Operating Condition	0.028	0.042	0.100	0.156
Alert Limit	0.010	0.156	0.255	0.396
Alarm Limit	0.156	0.396	0.396	0.622
Absolute Fault Limit	0.260	0.400	0.620	1.000

* Applicable to a machine with running speed between 600 to 12,000 rpm.
Narrowband setting: 0.3× to 3.0× running speed.
Machine Class Descriptions:

Class I Small machine-trains or individual components integrally connected with the complete machine in its normal operating condition (i.e., drivers up to 20 horsepower).
Class II Medium-sized machines (i.e., 20- to 100-horsepower drivers and 400-horsepower drivers on special foundations.
Class III Large prime movers (i.e., drivers greater than 100 horsepower) mounted on heavy, rigid foundations.
Class IV Large prime movers (i.e., drivers greater than 100 horsepower) mounted on relatively soft, light-weight structures.

Source: Derived by Integrated Systems, Inc. from ISO Standard #2372.

Figure 2.Trigger levels from vibration results. Table 7-2 from Keith Mobley's "Plant Engineering: An Introduction to Predictive Maintenance" [11].

The best way to monitor the condition of electrical equipment is with IR scans, also called thermography. Since handheld thermal imaging cameras are inexpensive and easy to use, it is most economical to perform IR scans in house. Data from IR scans are useless without a baseline reading. All parts that are scanned in the baseline and their associated temperatures should be entered in the CMMS. Comparing every new scan to the baseline will help diagnose problems like: "contact problems, unbalance current distributions, cracks in insulators, defective relays or terminal blocks, etc." [6]. A good place to start IR scans is drive cabinets and motor control center (MCC) busses for "mission critical" assets. When scanning a cabinet, Mobley recommends that the technician "scan cable, cable connections, fuse holders, fuse circuit breakers, and bus" [11]. As much as 45% of the failures detected are going to be from connections or contacts [8]. Although these problems can often be fixed simply by tightening the contact or cleaning it, the problem should still be tracked in the CMMS. The technician can tell when the contact has a failure because the temperature is higher than the wire going to it [11]. See Table 1 for a general guide on when to change equipment based on the results of an IR scan.

Table 1. Summary of when to change equipment when a failure is found during and IR scan. Guidelines based on recommendations from Lizák, et al [8].

Temperature	Seriousness
Greater than 130°C	Shut down to change equipment
Between 100°C and 130ºC	Change on next scheduled shutdown
Between 75°C and 100º C	Change when convenient

Methods

In 2014, Fitesa Washougal (or Washougal) started to make a shift from a mix of RTF and PM to a mix of PM and PdM. At the Washougal plant there were already IR scans of electrical cabinets being done; however, they were only done annually. The company also had a CMMS in place, but only the storeroom functions were being used. The CMMS was not user-friendly, and was only used by a couple of employees. Neither Work Orders nor PMs were being consistently tracked.

The first step the maintenance team took was to create a user-friendly, computerized work order system. This was done with a simple HTML site that allowed both salaried and hourly staff to enter work they believed needed to be done on the machine. An example of a work order produced by this system is shown in Fig. 3.

Figure 3.Example of a work order created by the HTML based work order system. Work orders can be created by any employee, and then the maintenance manager assigns them to technicians.

This new system made tracking and assigning work easier; however, the work orders were not tied to a specific asset, did not include parts needed, did not have time estimates, and were not automatically generated for PMs. The need for a new CMMS system became apparent, and MACMMS™, a web-based platform, was purchased.

The maintenance team then started entering assets into the new CMMS, a process that is still underway. Priority was given to "mission critical" assets. MACMMS™ allows the user to categorize equipment by creating an asset tree. Figure 4 is an example of the asset tree for Washougal's calender motors.

Figure 4. Asset tree for calender motors in MACMMSTM. If the motor number for the Top Emboss Roll were unknown it could easily be found by knowing the Emboss Roll is part of the Calender Stack which is part of Line 3.

The CMMS also allows the user to designate an asset as online or offline, which has been beneficial in tracking Washougal's AC and DC motors. Prior to this system, the motors were tracked in a simple Excel file, which is shown in Appendix A. The information from this file was checked for accuracy, and then put into the CMMS. As motors are swapped a user designates it as "offline" and adds a comment as to why it was removed.

In previous years, an effort had been made to catalogue the PMs that the millwrights perform. This catalogue was kept as an Excel file, complete with detailed pictures. An example is shown in Appendix A. The PMs were entered into the new system, tagged to the appropriate asset, and given a time estimation. The CMMS automatically generates a PM work order according to the schedule laid out in the Excel files. The PM work order is printed out and given to the maintenance lead, who assigns the work, and when the work is completed the work order is closed by the salaried maintenance staff.

Washougal had previously purchased an IR Camera, and the decision was made to start doing in-house IR scans on the electrical cabinets and MCC buses. The IR camera purchased is a Milwaukee 2260-21NST, which can be purchased at grainger.com for $3,567. The maintenance team determined that the most critical equipment were in the drive and PLC cabinets. The drive and PLC cabinets associated with Washougal's extruders were the first to get a baseline reading. The IR camera comes with software that allows the user to easily analyze the data. After the picture is taken the user can load the images into the software and find the temperature of any part of the picture. An example from an IR tour done in January 2015 is shown in Appendix B.

Next, a work instruction was written to standardize the data gathering process. The work instruction has each component numbered; the corresponding picture number allows the user to identify the component. Appendix B has an example page from this work instruction. When analyzing the results of the scan, attention is paid to the terminals, and average temperatures of the components are entered into the CMMS. The readings can be exported from the CMMS to a CSV file where they can easily be tracked and used to make a trend.

The other PdM method used by Washougal is vibrational analysis, which is contracted to an outside company. The contractor uses a portable accelerometer to scan older bearings on the machine and some mission critical motors. Currently, Washougal is scheduled for monthly vibration analysis, which has allowed them to start cycling out bad fly rolls and process motors.

On February 25th, 2015 a vibration analysis concluded that a motor driving a suction blower needed to be changed on the next scheduled downtime. This conclusion was based on elevated vibration in both the drive end and opposite drive end bearing. On March 6th there was a planned machine shut down for a product change where Motor 1012 was changed. This caused no additional maintenance downtime. This is in contrast to an unscheduled motor change on similar equipment which took 150 minutes of maintenance downtime on February 24th. This motor was not part of the PdM program. Figure 5 shows the vibration data from February 25th, 2015. The peak frequency shown is 0.5302 in./sec. According to Fig. 2 this should be less than 0.156 in./sec.

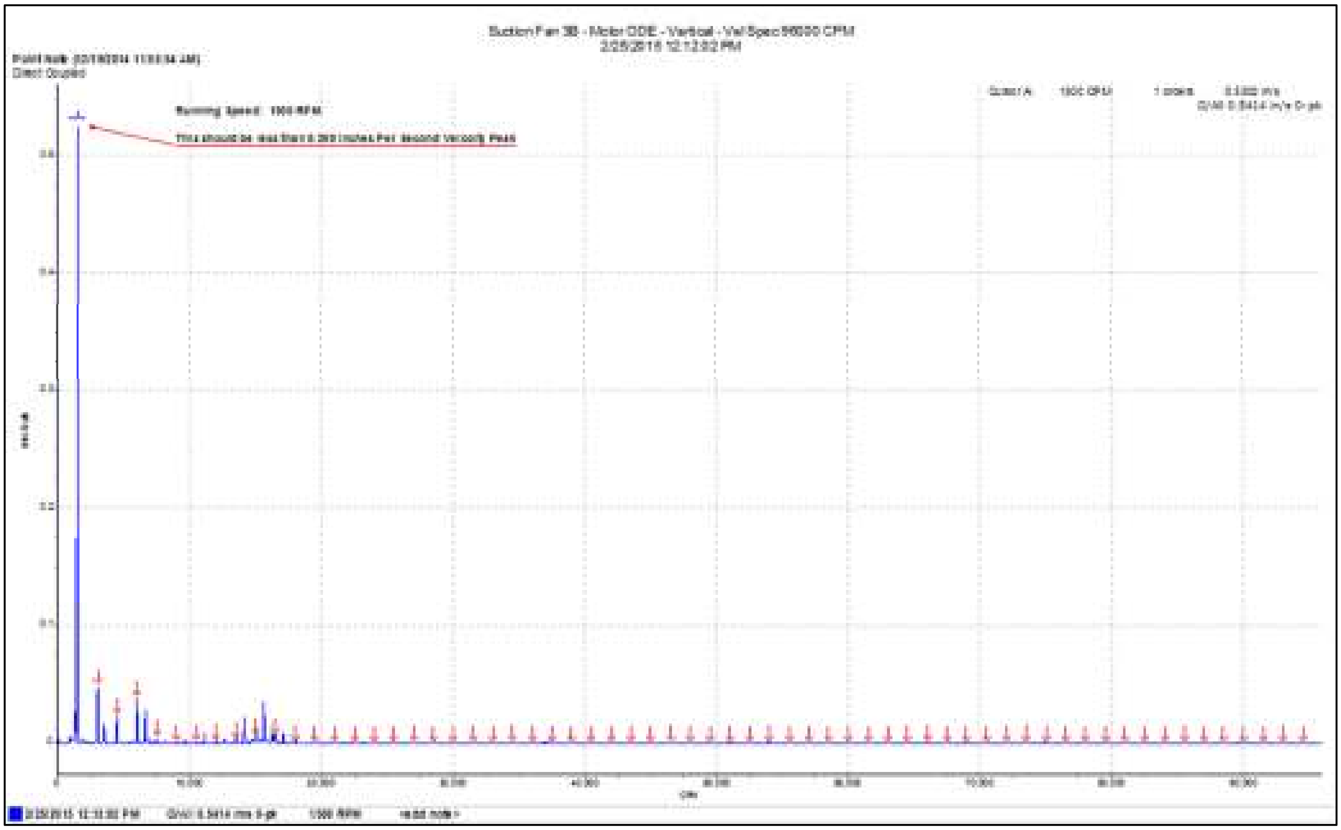


Figure 5. Vibration data taken on February 25th, 2015. The reading of 0.5414 in/sec peak is significantly higher than the target of 0.156 in/sec.

Results

To analyze the effectiveness of Washougal's PdM efforts a number of key metrics were compared to a baseline. These metrics are: Uptime, Maintenance Downtime, Percent Preventative Maintenance, and Maintenance Spending. The baseline is defined by the average of these metrics for 2013 and the first six months of 2014. The plant did not start implementing the bulk of its PdM program until July 2014. All metrics are presented as a percentage of the baseline to keep actual values confidential.

Uptime is the metric most used to evaluate the maintenance department. Uptime is defined by Equation 1.

$$Uptime = \frac{Machine\ Run\ Hours}{Machine\ Run\ Hours + Machin\ Down\ Hours} \tag{1}$$

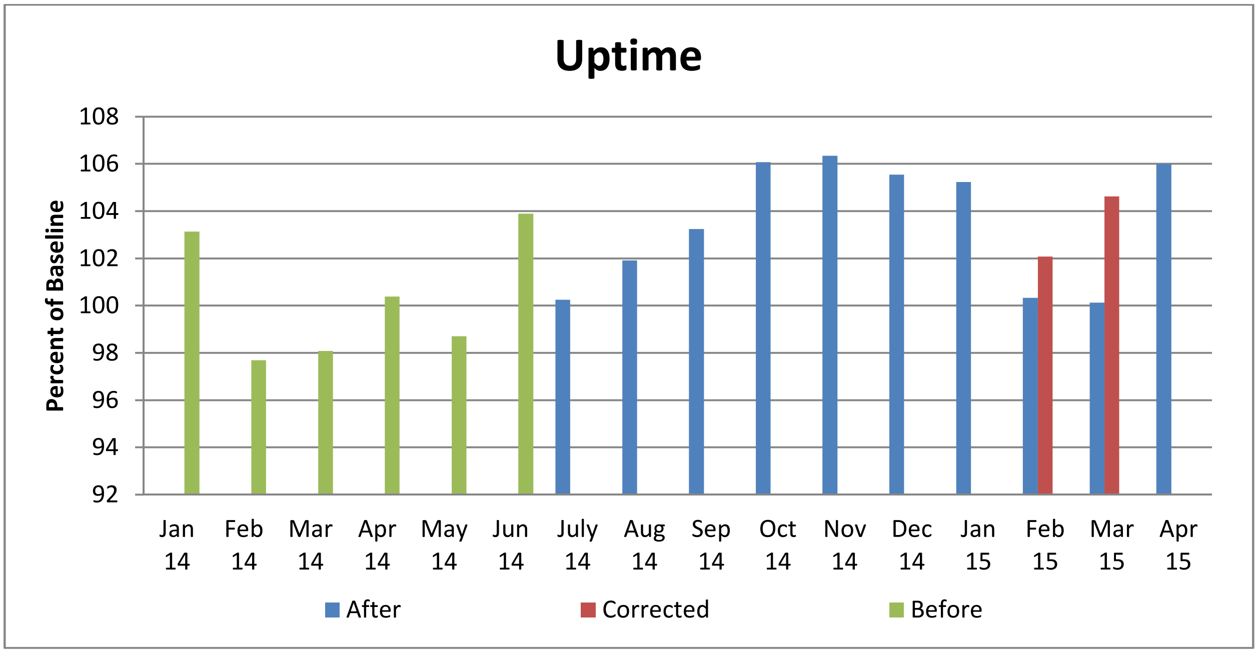


Figure 6. Uptime as a percent of baseline for 2014 and the first four months of 2015. The red bars are a corrected value accounting for four major downtime events associated with one piece of machinery.

Figure 6 shows the trend in increased uptime after PdM implementation. In February and March 2015 there were four unplanned maintenance downtime events related to one motor. This resulted in a total of 40 hours of unplanned maintenance downtime. This motor was underneath the machine, and could not be reached with either an IR camera or a handheld accelerometer. A corrected value for February and March are also presented in Fig. 6 which does not include these four events. The motor has since been mounted on the outside of the machine and is now covered in the predictive maintenance program.

There is a clear trend shown in Fig. 6 of increased uptime between August 2014 and January 2015. If the corrected values are used this trend continues to April 2015. In total there was a 3.5% increase in uptime between July 2014 and April 2015 over baseline. This number increased to 4.1% with the corrected values. For a plant with a single machine, these numbers translate into a significant increase in EBIDTA.

Uptime is used to assess the effectiveness of both the operations department and the maintenance department. There is a certain amount of causal link between the two; however, which is why they are generally grouped together. In order to focus more on the maintenance department a metric called "Maintenance Downtime" is used. This metric is simply downtime caused by scheduled and unscheduled maintenance downtime over the total downtime. To compare scheduled maintenance downtime to unscheduled maintenance downtime Washougal uses the metric "Percent Preventative Maintenance". This metric is defined by Equation 2. These two metrics are shown in Fig. 7.

$$\%PM = \frac{Scheduled\ Maint.Downtime}{Total\ Maintenance\ Downtime} * 100 \quad (2)$$

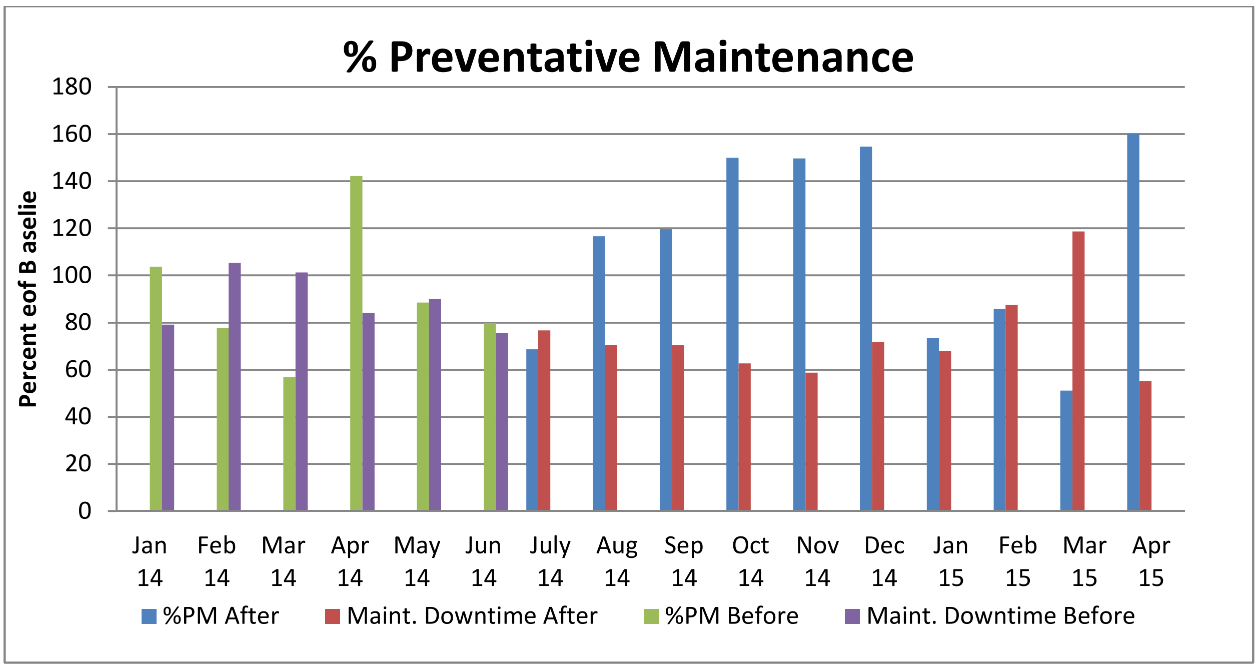


Figure 7. Total Maintenance Downtime and Percent Preventative Maintenance for 2014 and the first four months of 2015. All values are a percent of baseline.

Figure 7 shows that even before full implementation of the PdM program Maintenance Downtime was better in the beginning of 2014 than baseline. However, more of the downtime hours were unscheduled than after PdM implementation. As mentioned above reactive maintenance costs two to four times proactive maintenance, so this difference translates into real savings. Since July 2014 there has been a 13% increase in Percent Preventative Maintenance. This is accompanied by a 26% decrease in Total Maintenance Downtime.

The one downside to implementing a PdM model is increased cost. As assets are identified to be replaced through IR scans and vibration analysis, maintenance costs can rise dramatically. There is generally an initial backlog of machinery that should have been changed long ago, but without the proper tools nobody knew just how bad their condition was. To show that this increase in costs also comes with increase in savings, Fig. 8 shows savings from lost production which is calculated using Equation 3.

$$Lost\ Production = \frac{Downtime\ Cost}{hr} * Maint.Downtime \tag{3}$$

Downtime Cost per hour is a calculated, and confidential, figure from Washougal's comptroller. Figure 8 shows that even though maintenance spending increased dramatically over baseline, savings from lost production was significant.

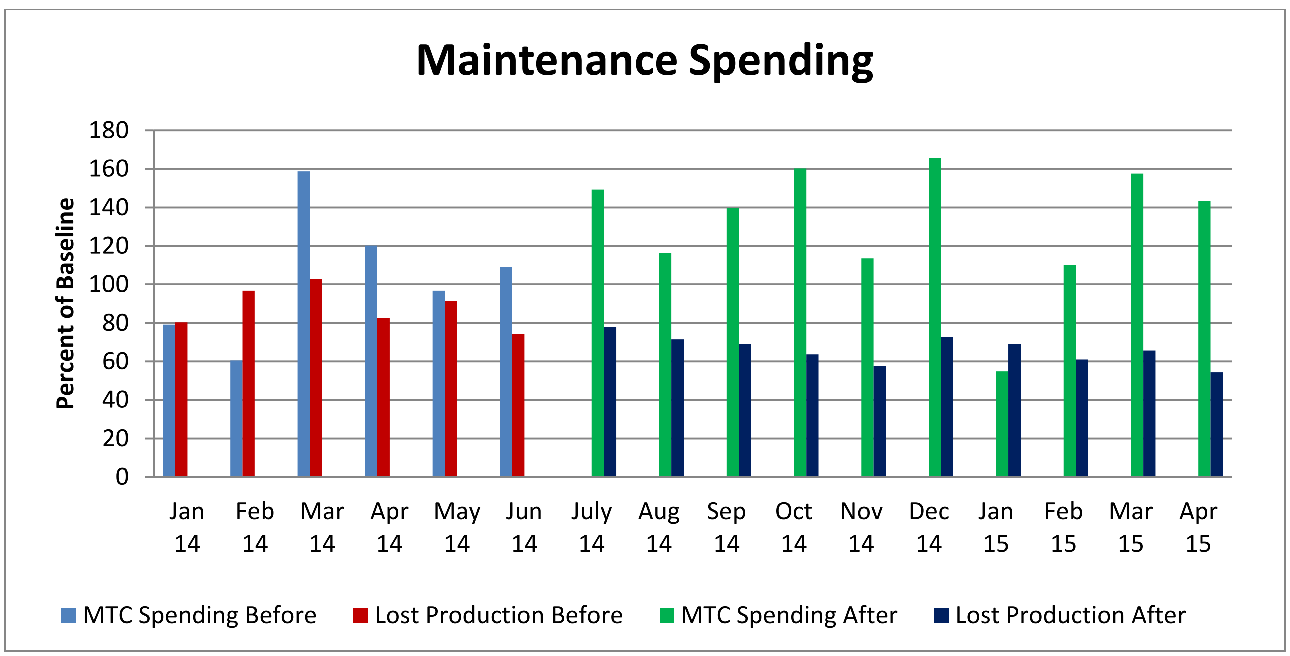


Figure 8. Maintenance Spending and Lost Production for 2014 and first four months of 2015

To show the cumulative effect of both increase in maintenance spending as well as decrease in lost production Equation 4 was used. As with most values that are calculated using a difference, this number swings widely month to month. To dampen some of this swing a rolling average was graphed in Fig. 8. This rolling average weights the current month 50%, previous month 35%, and two months prior 15%. Similarly to above, a corrected value accounting for the four motor events in February and March 2015 is shown.

$$Net\ Savings = (Baseline\ MTC\ Spend - Actual\ MTC\ Spend) + (Baseline\ \ MTC\ Downtime - Actual\ MTC\ Downtime) * \frac{Downtime\ Cost}{hr} \tag{4}$$

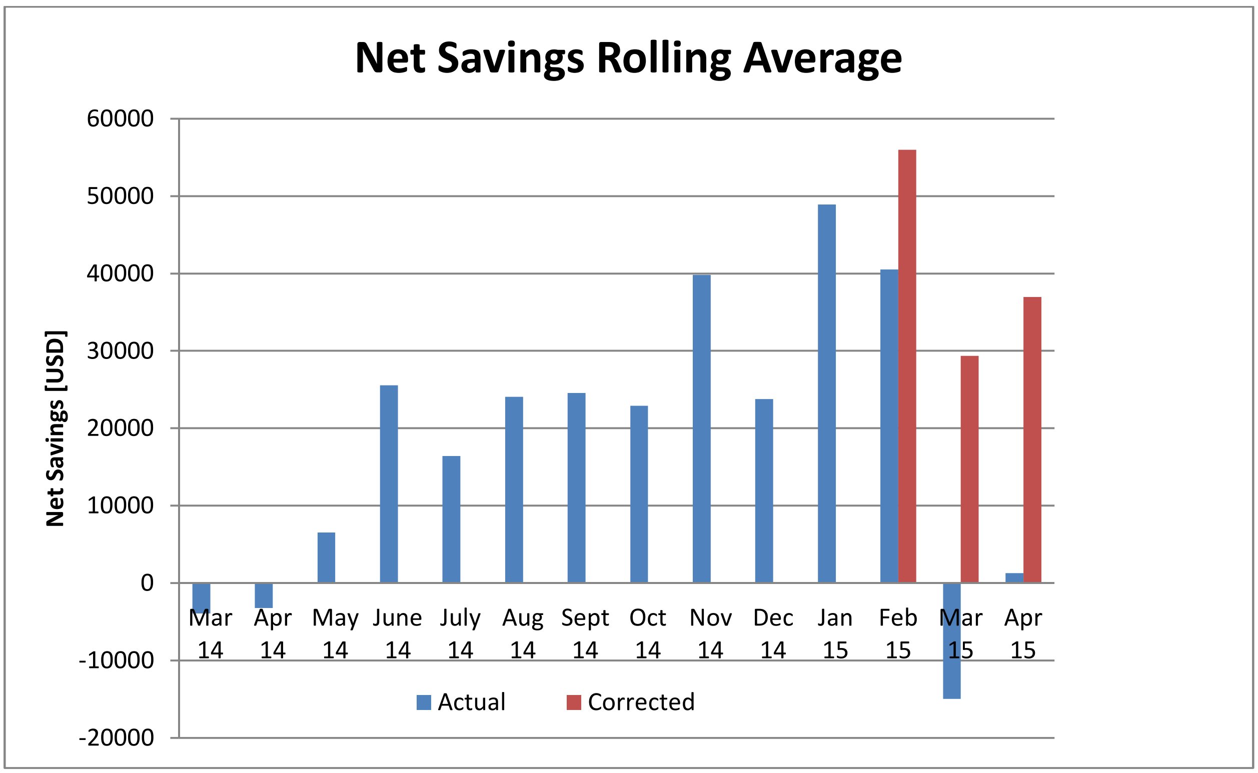


Figure 9. Rolling average of net savings from increase in maintenance spending and decrease in lost production. The red bars show a corrected value accounting for the 40 hours of downtime associated to one piece of machinery.

Figure 9 shows that even though maintenance spending for July through December was significantly above baseline, the decrease in lost production resulted in a net positive. This adds up to a yearly savings of $267,000 over baseline. This number increases to $406,000 per year using the corrected values.

Further Recommendations

Significant progress was made at Fitesa Washougal to move to a Predictive Maintenance Model. But more work must to be done to get to a "World Class Maintenance Program" defined in Table 2.

Table 2. Defining Characteristics of a World Class Maintenance Program [3].

Vibration Program	63%-95% of rotating machinery
IR Scan	91%-100% of electrical equipment 58%-79% of mechanical equipment
PMs	20%-25% of equipment
Work Orders Hours	50% PdM -15% Condition collecting -35% PdM Corrective 30% PM -15% Collecting Data -15% PM Corrective 20% Reactionary
Wrench Time	50% compared to 28%

Washougal's current vibration program covers an estimated 40% of rotating machinery. Increasing this number to the goal of 95% would be extremely expensive and time consuming using the current methods. Permanent accelerometers need to be mounted on machine bearings and process motors. This would allow a technician to gather all the data at a couple of terminal blocks in a fraction of the time. A member of Washougal's maintenance team should also be trained to gather and analyze the data instead of the work being contracted to an outside company.

The IR program currently covers an estimated 25% of all electrical equipment. The main deterrent to expanding this program is manpower. Cataloguing and doing baseline readings for all the cabinets and MCC busses is extremely time consuming. An electrician is required to be present while the electrical panels are open; therefore, this work can only be done when there is a free electrician. The initial cataloguing of the equipment could be done by an outside company with more experience. The outside company could also provide recommendations for temperature tolerances and reading intervals. However, this work would be extremely expensive.

Improving the CMMS would be the quickest way to realize savings. As stated in the review of the literature there can be up to a 50% savings in maintenance spending with a good CMMS. Washougal's CMMS needs more user accounts so that work can be assigned to specific users. This would allow the maintenance manager to more efficiently schedule the maintenance team's daily, and downtime, activity. The mechanics and electricians need to be trained to register their own work in the CMMS. For example, electricians should be trained to register a motor swap, and mechanics should be trained to check off PMs as they are completed. MACMMS produces a QR code for each asset, an iPad could be used to scan this code and register the work.

Conclusion

The results from Fitesa Washougal's implementation of predictive maintenance show that significant savings can be realized within one year with minimal initial investment. Ten months into the program Washougal is seeing a net savings of $267,000 per year. This savings is due to the 3.5% increase in uptime. The downtime caused by maintenance activities decreased a total of 26%. The amount of that downtime that was planned increased by 13%. Three main predictive maintenance techniques were used to get this increase in productivity: upgrading the CMMS, IR scans, and vibration analysis.

Once a good team has been selected to lead the change to a predictive maintenance model, the company's CMMS should be looked at for potential upgrades. For many companies their current CMMS is not user-friendly. A good CMMS can lead to significant reductions in maintenance spending. Next, the team should identify assets that should be covered by a PdM program. Many of these assets are already covered by a PM program, which is more expensive than PdM.

In July 2014 Fitesa Washougal implemented the bulk of their new PdM model. A new CMMS was purchased which allowed the maintenance team to keep better track of the company's assets. Asset trees were created and entered into the CMMS. New work orders are tied to these assets, which gives the team a record of all work done on an asset. Using this new CMMS and doing regular vibration analysis and IR scans decreased the downtime on Fitesa's machine. Washougal could improve on these results by continuing to expand their PdM program. Expanding the program would require substantially more investment in the maintenance department, and the results from the past ten months show this investment will have a substantial return.

References

[1] Belanger, Dennis. “Top Five Maintenance & Reliability Enablers for Improved Operational Performance”. 2012. Management Resource Group, Inc. Web. 3 March 2015.

[2] Crain, Mike. "The Role of CMMS." *Industrial Technologies Northern Digital, inc* (2003).

[3] DiStefano, Robert. “Elevating Maintenance and Reliability Practices: The Financial Business Case”. 2002. Management Resource Group, Inc. Web. 1 March 2015.

[4] Hashemian, H.M.; Bean, W.C., "State-of-the-Art Predictive Maintenance Techniques". *Instrumentation and Measurement, IEEE Transactions on*, vol.60, no.10, pp.3480, 3492, Oct. 2011

[5] Hart, Douglas. “Implementing a ‘Best Practices’ Predictive Maintenance Program: Avoiding the 10 Most Common Pitfalls”. 2012. Management Resources Group, Inc. Web. 5 March 2015.

[6] Huda, AS Nazmul, and Soib Taib. "Application of Infrared Thermography for Predictive/Preventive Maintenance of Thermal Defect in Electrical Equipment. "Applied Thermal Engineering 61.2 (2013): 220-227.

[7] Labib, Ashraf W. "A Decision Analysis Model for Maintenance Policy Selection using a CMMS." Journal of Quality in Maintenance Engineering 10.3 (2004): 191-202.

[8] Lizák, František, and Michal Kolcun. "Improving Reliability and Decreasing Losses of Electrical System with Infrared Thermography." *Acta Electrotechnica et Informatica* 8.1 (2008): 60-63.

[9] Lukas, Malte, and Daniel P. Anderson. "Machine and Lubricant Condition Monitoring for Extended Equipment Lifetimes and Predictive Maintenance at Power Plants." *Proceedings of Power-Gen International, Jakarta, Indonesia* (1996).

[10] Mitchell, John S. "From Vibration Measurements to Condition-Based Maintenance." *Sound and Vibration* 41.1 (2007): 62.

[11] Mobley, R. Keith. Plant Engineering: An Introduction to Predictive Maintenance (2nd Edition). Burlington, MA, USA: Butterworth-Heinemann, 2002. ProQuest ebrary. Web. 9 Feb 2015.

[12] Mobley, R. Keith. Maintenance Engineering Handbook (Eighth Edition). New York, NY. McGraw-Hill Education, 2014. Access Engineering. Web. 11 Feb 2015

[13] Penny, Janelle. "Fast-Track Your Maintenance Practices." *Buildings* 106.10 (2012): 36-40. *Vocational and Career Collection*. Web. 4 Mar. 2015

[14] Pinkard, Jerry. "Implementing your PdM Program: Is Your Program Capable or Reliable". 2013. Management Resources Group, Inc. Web. 20 Feb. 2015

[15] Smith, Rusten. "BOM Best Practice Analysis- The Missing Tool for Maintenance and MRO Inventory Control". 2013. Management Resources Group, Inc. Web. 16 Feb. 2015

[15] White, Timothy. "Applying the Correct Maintenance Strategies to Your Assets". 2012. Management Resources Group, Inc. Web. 15 Feb. 2015.

[16] Wirema, Terry. "Managing Predictive Maintenance: PdM is only effective when it's an integral component of a complete maintenance strategy." *Plant Engineering* Oct. 2003: 58+. *General OneFile*. Web. 16 Feb. 2015.

[17] Wray, Ian. "Integrating EAM and PdM for Maintenance Productivity." *Plant Engineering* Oct. 2003: 65+. *Business Insights: Global*. Web. 16 Feb. 2015.

Appendix A: Motor List and PM Catalogue Example

Table 1A. AC Motors currently running in the machine. This Excell file was used to add the motors to the CMMS.

LOCATION	HP/KW	RPM	FRAME	VOLT	AMPS	MFG	TYPE	CODE	CLASS	MODEL	ENCL	SERIAL
Attached to #988	0.27	2950		460	0.29	Siemens	Cooling Fa			W2D250-EA26-05		
A-10	0.33	1725	56C	115/230	6.0/3.0	Baldor		L	B	34G63-5507	TEFC	W6-9J
E-27	0.33	3450	56C	230/460	1.8/0.9	General Electric		P		5K33FN41A		PFL251868
C-10	0.33	3450	56CZ-60			Marathon					TEFC	
E-21	0.5	1725	56C	230/460	2.0/1.0	Baldor		L	B	34A63-872	TE	W897
E-21	0.5	1725	56C	230/460	2.0/1.0	Baldor		L	B	34F10-872	DP	W2-93
E-21	0.5	1725	56C	230/460	2.0/1.0	Baldor		L	B	34F10-872	DP	W2-93
C-40	0.5	1075	48YZ			Dayton				4M197		
F-10	0.75	1725	56C	230/460	2.6/1.3	Baldor		L	B	TBDP	TE	W699
E-21	1	3450	56C	230/460	3.6/1.8	Baldor		H	B	34A62-282	TEFC	W897
E-21	1	3450	56J	230/460	3.2/1.6	Baldor		L	B	34K36-3226	TEFC	W12-94
E-21	1	3450	56J	230/460	3.2/1.6	Baldor		L	B	34K36-3226	TEFC	W12-94
D-34	1	1140	56C	230/460	3.4/1.7	Baldor		C	B	35A12-1272		
D-7	1	1725	56C	230/460	3.4/1.7	Baldor		J	B	35E58-87-B	TEFC	F497
F-10	1	1725	56C	230/460	3.2/1.6	Baldor		L	F	35H833Y102	TENV	F0106202108
A-10	1	1720	56C	230/460	3.6/1.8	Leroy-Somer		L	B	C2EY40	TEFC	D5512695
D-7	1	1750	143TC	230/460		Baldor				ZDWNM3546T		
A-1 Conv. Line 3 Rew Upend 140 CDLR	1	1700		230/460								
D-13	1	1755	143T	460		Emerson						
F-10	1.74	3435		460		Siemens						
E-33	2	1740	145T	230/460	5.6/2.8	Baldor		K	B	35A001T585H1	TEFC	F0108011363
C-20	2	1725	145T	230/460	6.2/3.1	Baldor		K	B	35A01-872	TEFC	
C-40	2	1720	DFT90L4	230/460	6.0/3.0	Eurodrive	Gearmotor			DFT90L4	TEFC	
C-20	2	1750	145T	230/460								
E-15	3	1765	182T	230/460	7.2/3.6	Siemens	RGZECH	K	F	104	TEFC	
E-21	3	3450	56C	230/460	7.6/3.8	Baldor		K	F	35A13T123	TEFC	F298
C-20	3	850	215T	230/460	12/6	Baldor		M	F	37A01-429	TEFC	
C-20	3	850	215T	230/460	12/6	Baldor		M	F	37A01-429	TEFC	
A-40	3	1725	D100LC	230/460	8.6/4.3	BALDOR				MVM3611C	TEFC	F0312160774
D-1	3	1800	WF182TC		8.6/4.3	Reliance				P18A6538P	TEFC	
D-1	3	1800	WF182TC		8.6/4.4	Reliance				P18A6538P	TEFC	
C-10	3	3495	90L	460	3.75	Lafert			F		TEFC	
G-20	3	1800	WF182TC			Reliance						
A-10	3	1800	WF182TC	230/460	8.6/4/3	Reliance	PMR	K	F		TEFC	
Storeroom E258301	4	5000	MD3450	230								
B-20	5	1800	184TC	115/230	24/12	Welco		D	F	3652	TEFC	60184
E-40	5	3450	184T	230/460	12/6	Baldor		K	F	36A01X100		
E-40	5	1725	184TC	230/460	13.2/6.6	Baldor		J	F	36A03W415	TEFC	F1098
B-10	5	1750	184TC	230/460	12.3/6.15	General Electric		J	F	5K184KD214B	TEFC	RWB30474
D-28	5	1800	184T	230/460	12/6	Welco			H	M-3754-H	TEFC	37482
B-30	5	1760	213TC	230/460		Baldor				ZDNM3767T	TE	
B-30	7.5	1745	213T	230/460	19.5/9.8	Siemens	RGZ1	G	F	120		900615207
F-20 (spare c-hook hyd motor)	7.5	1765	213TYZ	460	10.5	Vickers				37L918T053G1	TEFC	
D-34	7.5	1750	213T	230/460	21.6/10.8	Marathon	TDR	H	B	LVK213TTDR7026GJW	DP	
D-40	10	1750	215T	230/460	24/12	Siemens	RGZESD	H	F			
F-30	10	1725	215TC	230/460	26/13	Baldor		J	F		TEFC	F285
E-40	10	1760	215T	230/460	28/14	Baldor		J	B		DPSB	F0203042295
B-40	10	1760	215T			WEG					TEFC ET	
J-20	15	1760	254T	230/460	34.0/17.0	Siemens	RGZE-CH	G	F	036	TEFC	51-386-315
B-40	15	1765	254T	460	19.0	General Electric	K	G	F	5K254SS208		
G-40	15	1765	254T	230/460	36/18	Baldor		H	F	EM2333T-NYB	TEFC	0599C0741
J-20	15	1750	254T	480	18.2	Allis-Chalmers	RGZ-CH	G	F		TEFC	51-307-615

fitesa	WORK INSTRUCTION	Document No.	

3A VACUUM BOX SUCTION FAN 2ND FLOOR PMS

DEPARTMENT	Maintenance		**Date**	2/2/2013
LOCATION	2ND FLOOR			-

3A VACUUM BOX SUCTION FAN 2ND FLOOR PMS

3A VACUUM BOX SUCTION FAN 2ND FLOOR PMS

NOTES	**Tools needed**
LUBRICANTS USED	
Texaco RB #2 Grease	

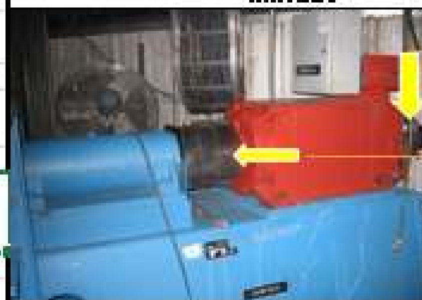
MACHINE STATE *DOWN AND LOCKED OUT*

1	Check inboard and outboard motor bearing for excessive heat or vibration.
2	Make sure guard is secure and in position.
3	Make sure motor external cooling fan is working with no unusual noises coming from fan. [bearings]
4	Feel inboard and outboard bearings in cartridge for
5	Keep fan exhaust screen clean of filaments.
6	Lube fan on a monthly basis.
7	Keep vacuum suction box room clean of dirt and

WHEN DOWN

LOCK OUT AND RELEASE ALL STORED ENERGY

IMAGES



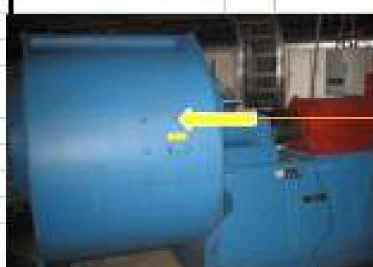
MOTOR COOLING FAN

COUPLING GUARD

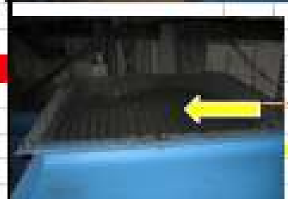
3A VACUUM BOX SUCTION FAN

INBOARD BEARING

OUTBOARD BEARING



FAN INSPECTION HATCH



EXHAUST SCREEN

Lock out		Belt #	**PERSONAL PROTECTION**
CABINET +413			WEAR REQUIRED PPE
+863 M01			

Figure 1A. Example from PM catalogue. PM for A-Beam suction fan.

Appendix B: IR Scan and Work Instruction

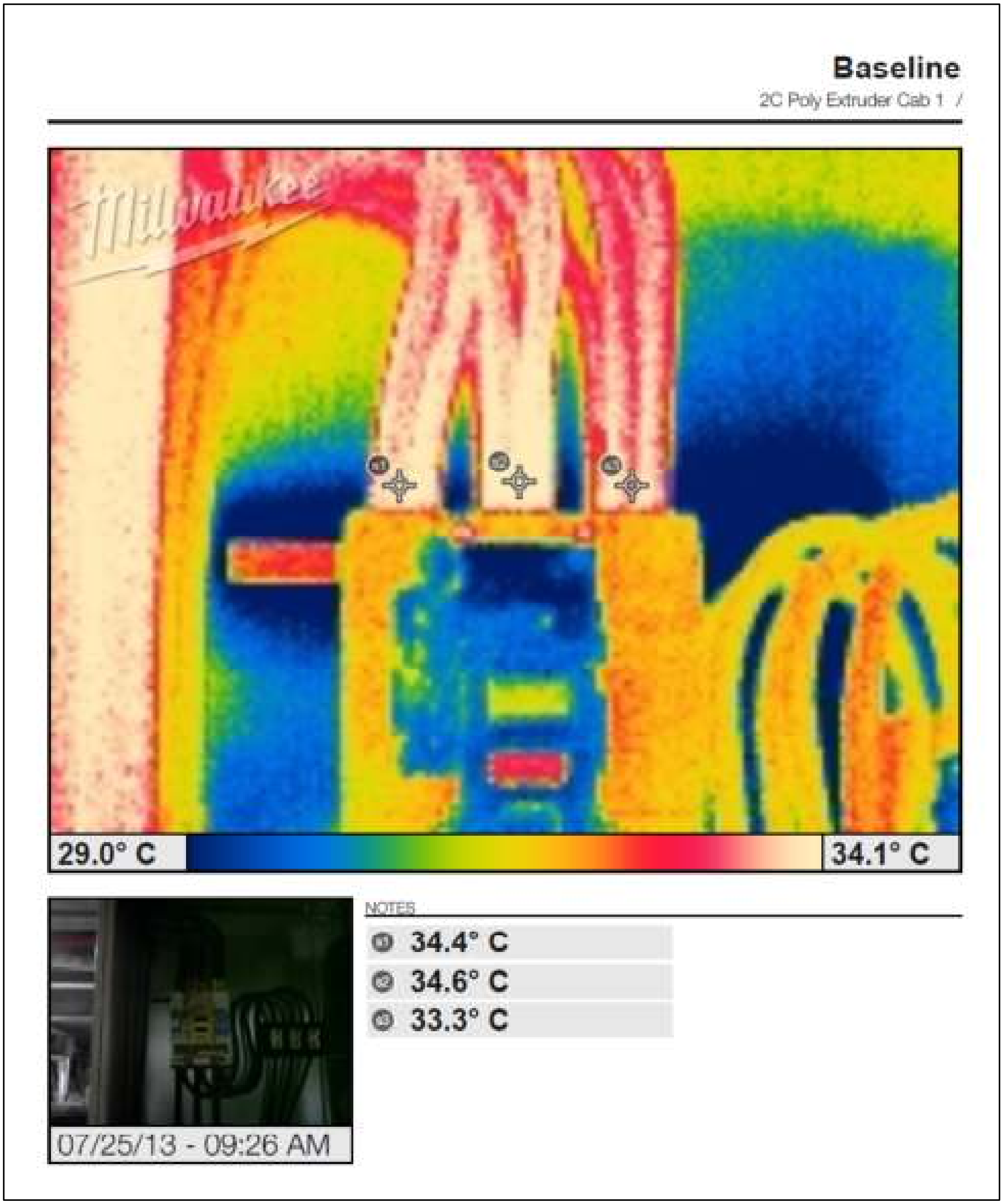


Figure 1B. Baseline reading of Circuit Breaker 2C in the 2A Poly Spin Pump Cabinet. Baseline readings were taken in July 2013.Regular IR scans did not start until July 2014.

3rd Floor IR Scan

Date:____________
Technician:____________

Poly 2A Spin Pumps Cab. #2

1	CB-2A
2	ESR-2A1
3	PDB-2A1
4	Spin Pump 2A1
5	Spin Pump 2A2
6	Spin Pump 2A3
7	Spin Pump 2A4
8	Spin Pump 2A5
9	Spin Pump 2A6

Figure 2B. Work instruction for taking pictures of 2A Poly Spin Pump Cabinet #2.